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Specification and Drawings, as originally filed, with Application for Patent Serial No: **2,434,735**, on July 7, 2003, by **DOFASCO INC.**, assignee of William Lindsay and Kevin Guy Hunt, for "Diagnostic Method for Predicting Maintenance Requirements in Rotating Equipment".

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ABSTRACT

This invention is a method that uses the electric signal drawn from a vibration sensor containing a piezoelectric crystal over a short period of time to generate a value. There is a reading taken when the spindle is loaded and at a steady state (same position relative to location of load in machine), and another taken when the spindle is unloaded and at steady state. Based on observations, a good spindle shows more energy when loaded verses unloaded. The opposite relationship is characteristic of a bad spindle.

DIAGNOSTIC METHOD FOR PREDICTING MAINTENANCE REQUIREMENTS IN ROTATING EQUIPMENT

FIELD OF THE INVENTION

This invention relates to monitoring of wear conditions on rotating shaft equipment in a plant environment, such as drive spindles for work rolls to reduce the thickness of cast metal slabs. It will however be understood that the invention will likewise find application for monitoring other types of rotating equipment, such as fans, motors, roll out tables, pumps, etc.

BACKGROUND OF THE INVENTION

It is common practice to monitor the spindles on rolling mills to avoid catastrophic spindle failures and resultant damage. Commonly, the spindles are monitored and replaced according to a time-based system. This, however, can provc inaccurate, as the wear on the spindles is dependent on loads and volume, which, in a plant environment, is continually changing. Therefore, spindles may fail before their scheduled replacement time due to increased loads or other problems that increase the rate of wear. As well, spindles may be replaced prematurely, simply because the scheduled replacement date has arrived. This results in a decrease in productivity, as well as increased maintenance costs.

Another method currently available for monitoring spindle wear is a wireless torque monitoring system. While effective, this system is costly and, therefore, users often find it too expensive to justify its implementation in large plant environments. Also, within plant environments, there is such significant damage to these systems that continuous replacements make them impractical.

One of the objects of this invention is to provide a relatively inexpensive, online method to monitor the condition and wear of rotating equipment using current equipment and less labour during routine maintenance to give an early warning of a change in operating conditions which may warrant further inspection and the eventual replacement of failing equipment.

SUMMARY OF THE INVENTION

In accordance with the invention, there is provided a diagnostic method for predicting maintenance requirements in rotating equipment normally operating in loaded and unloaded conditions, the method including the following steps: coupling a sensor to apparatus associated with said rotating

equipment, said sensor being responsive to vibration in said apparatus to generate an electric signal; obtaining a load signal from apparatus associated with said rotating equipment which is indicative of whether the rotating equipment is loaded; sampling said electric signal when the rotating equipment is loaded over a predetermined sampling period of time to obtain a loaded electric signal V_ℓ; sampling said electric signal when the rotating equipment is unloaded over a predetermined sampling period of time to obtain an unloaded voltage signal V_μ; and periodically displaying the relative magnitude between said loaded electric signal V_ℓ and said unloaded electric signal V_μ over an extended maintenance period of time, a maintenance inspection being required when the unloaded electric signal V_μ exceeds said loaded electric signal V_ℓ.

Brief Description Of The Drawings

In order to better understand the invention, a preferred embodiment is described below with reference to the accompanying drawings, in which:

Fig. 1 is a diagrammatic sketch of a drive train for a mill roll stand;

Fig. 2a is a plot showing raw sensor data in millivolts collected from a piezoelectric sensor mounted to a pinion gear box against time in seconds showing a worn spindle signature;

Fig. 2b is a similar plot to Fig. 2a drawn over a shorter period of time for an unloaded data point of Fig. 2a;

Fig.3a is a similar plot to Fig. 2a after replacement of a spindle showing a new spindle signature;

Fig. 3b is a similar plot to Fig. 3a drawn over a shorter period of time for an unloaded data point of Fig. 3a;

Fig. 4 is a performance chart for the mill stand of Figs. 2 and 3 plotting values of ΔV over a period of six weeks;

Fig. 5 is a performance chart for a different mill stand (#2) showing normal behaviour after a spindle replacement;

Fig. 6 is a performance chart for a different mill stand (#3) showing mechanical problems observed in a gear box; and

Fig. 7 is a performance chart for a different mill stand (#4) showing normal behaviour after a lubrication correction.

Description Of Preferred Embodiment

The invention will be described with reference to a specific application for monitoring the condition of drive spindles used in a hot mill. It will be understood that the invention may find applications

in other environments which include rotating equipment that operates in loaded and unloaded conditions.

In a finishing mill rolling process, hot strip steel is threaded through several mill stands, which are individually driven. The rotating speed of mill drives increases as strip progresses through the process. The steel 16 is compressed and rolled out as it travels through each mill stand to achieve the desired gauge, shape, and length.

A typical drive train 18 is described with reference to Fig. 1.

A motor 20 drives a set of two identical pinion gears (not shown) in a gearbox 22, which are connected to two (top, bottom) drive spindles 24, 26. Top and bottom work rolls 28, 30 are inserted into the roll end casings 32, 34 of the drive spindles 24, 26 and are driven by the drive train. A set of work rolls 28, 30 then become the driving force for the larger backup rolls 36, 38 as force is applied to the roll stack by screws on the top of the mill.

AC power is provided to two sensors 40, 42 mounted to the pinion gear box 22 at spaced locations adjacent to the associated pinion gears (not shown). The crystals in the sensors are excited by vibration at the gearbox which induces a voltage signal. The voltage signal received from the sensors is sent to a PC where software is used to extract the desired information from the raw voltage signal.

Piezoelectric crystals are used in vibration sensors partially because of their ability to generate an electric signal. A 24 V AC signal is sent to the sensor, whose response is a millivolt DC reply. Piezoelectric crystals are used in vibration sensors due to their fast response to impacts, creating a voltage response representing the frequency range of the sensor. Each vibration sensor has a different frequency range depending upon the model and manufacturer. Typically vibration manufactures produce sensors with large frequency ranges so the customer can manipulate the signal through monitoring equipment (meters). With this invention, we are only using data from the sensors within a narrow predetermined maximum frequency range via a filter. Once enough data is received, another pulse is immediately sent out. Only a narrow frequency response is recorded based upon the rotational speed of the equipment and problem being identified.

Normally, the feedback data from this crystal is subjected to calculations and returns values that indicate the measure of vibration in engineering units. The method prescribed by this invention suggests ignoring the conversion of signal to engineering units, and instead, uses the electrical signal (voltage) the crystal produces as the raw data. Accelerometers are preferred over velometers as sensors, except for very low speed applications where the high cost of using a velometer may be justified. However, different types of sensors would simply generate different values, and since the values are only relative to the machine from which they are output, any sensor can be used provided it is used consistently on that piece of machinery.

The theory that any rotational equipment will exhibit a "power spectrum" was developed. A "power spectrum" is defined as the voltage sum of a short reply. It was found that any such equipment shows a low frequency signal that changes depending upon the equipment's state and condition. While this is not a specific mode of vibration, it is an energy signal in a selected frequency range. A cutoff frequency is determined via normal vibration readings (eg. 250 Hz maximum). In this particular case, the slower the equipment rotates, the lower the cutoff frequency. The vibration Fast Fourier Transform spectrum can quickly be used to determine the cutoff value. The required equipment is a standard computer and an analog band filter (250 Hz) which can be purchased from catalogues.

The sum of the frequencies, as described above, provides a number, known as the power spectrum. For each sample, two power spectrums are recorded. One spectrum must be measured when there is a load on a spindle, while the other must be measured when the spindle is unloaded. These measurements are done at a steady state, which is approximately the last eighth of rolling (loaded) and the first quarter of the idling (unloaded), typically for a period of ten seconds.

Thus, a piece of data is extracted at two points during the rolling of each piece on every mill stand in the rolling sequence. The first piece of data V_ℓ is taken once the mill has achieved top speed, and the roll stack is under full load. The second piece of data V_μ is extracted after the steel exits the mill, and roll stack is no longer under the load (force) applied to the mill screws. The voltage amplitude recorded from the second (unloaded) collection point is then subtracted from the voltage amplitude recorded from the first (loaded) collection point. A daily average of these values ΔV is calculated and plotted on a performance chart. Typically, over 600 pieces are rolled each day and these 600 individual points are averaged to produce the single point shown on the graph. An alarm value is set to warn personnel of potential problems relating to spindle wear. If a daily, charted value falls

withing the range of alarm values an e-mail is automatically generated and sent out to required personnel. At this point, further investigation of any potential problems can take place.

The failure mode being monitored is wear in the roll end casing of the spindles, which are a spline fit. The theory behind the analysis method is that in a healthy spindle, vibration recorded at the sensor location should be greater in amplitude in the top speed, full load condition than when the mill speed is reduced with no load applied.

In the following examples, the data used to create the plots of Figs. 2 and 3 was obtained using a real time analyzer having a 200 Hz filter whereas the data used to create the performance charts of Figs. 4 to 7 was obtained using other equipment with a 250 Hz filter. As a result, the magnitude of the voltage readings used to create the performance charts of Figs. 4 to 7 is a relative value which differs from the voltage readings plotted in Figs. 2 and 3. Since it is the difference in voltage readings between the unloaded collection points and the loaded collection points which is being plotted, the charted trends are consistent in that positive values are considered "good" and negative values are considered "bad".

As explained in the data collection process, daily chart values ΔV are recorded by subtracting the top speed, steel in mill vibration amplitude from the low speed, no steel in mill amplitude.

A positive chart value ΔV indicates a healthy spindle, and a negative chart value ΔV would be an indication of spindle wear.

Examples:

(FIG 2) MILL STAND #7

Dual plot shows a signature from Pinion Box #7 taken from a CV 395 real time vibration analyzer. Top plot (FIG 2a MILL STAND #7) shows 94.4 second of raw data collected from the sensor 40 closest to the top drive spindle 24. The unit of measurement is volts. The two data points are marked, data point #1=0.017 volts V_ℓ, data point #2=0.081 volts V_μ. The bottom plot on FIG 2b shows an expanded view of data point #2 V_μ. The impacting occurs at the rotating frequency of the spindle. The spindle impacting is a result of looseness, which results in increased amplitude in voltage signal received from data point #2 V_μ. This looseness shows up clearly after the steel exits the mill and the spindles are no longer held tight on the roll end by the force applied to the roll stack.

The calculation for the daily charts data point #2 V_{μ} minus data point #1 V_{ℓ} would result in a negative chart value - 0.064 volts, which would generate an alarm.

(FIG 3) MILL STAND #7

Spindles were changed on mill stand #7, on recommendation based on vibration data. FIG 3 top plot shows 94.4 seconds of data taken at the same location on the pinion box as the data in FIG 2, again the unit of measurement is in volts. Data point #1 V_{ℓ}, 0.039 volts minus data point #2 V_{μ}, 0.005 volts. The daily chart calculation would be + 0.034 volts (IS note: chart Fig. 4 shows 0.4). This indicates that the spindle change was successful, and the chart value would be a positive value, and therefore no longer generate an alarm.

(FIG. 4) MILL STAND #7

The performance chart of Fig. 4 above shows calculated daily averages from data as described in "data collection" typically for a period of six months. Data shows deterioration of spindle on mill stand #7, as per the data in FIG 2 resulting in a negative chart value. At the point of alarm (zero) an email is sent to alert the required personnel, and a detailed vibration analysis is completed. A decision is made based on this information to change the spindle set at the next maintenance opportunity. This example wore out very rapidly at the end. This is normally not as rapid and can be allowed to slip to a value of -0.2 before true catastrophic failure. This one was changed due to a maintenance opportunity. Normally a spare would be ordered after remaining at 0 for more than three days and there would still be a couple of months of useful life left in the spindle (even in the faster stands which wear more rapidly than the slower stands).

The rate of change on the chart is also a factor in evaluating the urgency of the problem. The new spindles show a positive daily calculated chart value of approximately 0.4 volts as illustrated in FIG 4, indicating a reliable spindle set is operating in mill stand #7.

The slope of the chart generated from a new spindle after a few weeks of service can be extrapolated to the zero point to provide an indication of remaining spindle life.

As a supplementary early warning feature, the direction of the slope taken through the charted daily values of Fig. 4 can change due to abnormalities in the drive train. If there is a mechanical problem present, the trend will change up or down depending on the problem. If the slope trends down due

to increases in unloaded vibration, there is either mechanical looseness in the spindles or roll set defects present. If the slope trends up due to increases in loaded vibration, there is either gearset problems, pinion bearing defects, lubrication defects in the pinion box, or roll set defects. Recognition of these events will trigger detailed vibration analysis. Once any abnormalities are corrected the trend will return to the normal slope/pattern of the spindle.

The performance chart for mill stand #2 shown in FIG 5 of the accompanying drawings shows a slow and predictable slope after installation of a reconditioned set of spindles. While the scheduled replacement time had expired, the chart indicates that ample service life remains of up to one year.

The performance chart for mill stand #3 shown in FIG. 6 of the accompanying drawings shows slow predictable wear of spindles with a removal prediction of several years. There are mechanical problems observed in the gearbox which cause the slope to move upwardly and change pattern.

The performance chart for mill stand #4 (IS note: actual data is #7) shown in Fig. 7 of the accompanying drawings shows a generally downward slope indicative of basic wear in the drive train. The upward slope at the beginning of the chart is indicative of a problem on the driver side which was corrected by lubrication. The predicted inspection deadline for determining the remaining service life of the pinions expires in several years.

Once any problem is detected, a full analysis would have to be conducted using real time diagnostic vibration techniques. This cannot be done all of the time, because it takes too long to process the data in real time. However, by limiting which stands for instance have to have the complete vibration monitoring system, the user has saved time and money.

Currently the readings for each are compressed into a daily average, allowing for long term projections of the overall condition of the spindles. This invention has the potential to do a piece-by-piece analysis, which could lead to this being used as a method of quality control. The view would be much more detailed and would show changes for products and roll sets.

CLAIMS:

1. A diagnostic method for predicting maintenance requirements in rotating equipment normally operating in loaded and unloaded conditions, the method including the following steps;

coupling a sensor to apparatus associated with said rotating equipment, said sensor being responsive to vibration in said apparatus to generate an electric signal;

obtaining a load signal from apparatus associated with said rotating equipment which is indicative of whether the rotating equipment is loaded;

sampling said electric signal when the rotating equipment is loaded over a predetermined sampling period of time to obtain a loaded electric signal V_{ℓ};

sampling said electric signal when the rotating equipment is unloaded over a predetermined sampling period of time to obtain an unloaded voltage signal V_{μ}; and

periodically displaying the relative magnitude between said loaded electric signal V_{ℓ} and said unloaded electric signal V_{μ} over an extended maintenance period of time, a maintenance inspection being required when the unloaded electric signal V_{μ} exceeds said loaded electric signal V_{ℓ}.

2. A diagnostic method according to Claim 1 in which the sensor is selected from the group comprising a velometer and an accelerometer.

3. A diagnostic method according to Claim 1 in which the electric signal generated is either amplitude or voltage.

4. A diagnostic method according to Claim 1 in which the sensor includes a piezoelectric crystal.

5. A diagnostic method according to Claim 1 in which the rotating equipment is a drive spindle for a work roll and the load signal is indicative of whether the work roll is applying pressure to a work piece or whether the work piece has exited the work roll.

6. A diagnostic method according to Claim 4 in which the electric signal is sampled during a sampling period of time selected to correspond to a predetermined vibration frequency range.

7. A diagnostic method according to Claim 6 in which the predetermined vibration frequency

range during which the electric signal is sampled 0 to 150 Hz for rotating equipment rotating at less than 100 revolutions per minute.

8. A diagnostic method according to Claim 6 in which the predetermined vibration frequency range during which the electric signal is sampled 0 to 200 Hz for rotating equipment rotating at up to 700 revolutions per minute.

9. A diagnostic method according to Claim 6 in which the predetermined vibration frequency range during which the electric signal is sampled 0 to 500 Hz for rotating equipment rotating at more than 1000 revolutions per minute.

10. A diagnostic method according to Claim 1 in which the said loaded electric signal V_ℓ is sampled over a period of 10 seconds during which the rotating equipment is fully loaded.

11. A diagnostic method according to Claim 1 in which the said unloaded electric signal V_μ is sampled over a period of 10 seconds during which the rotating equipment is unloaded.

12. A diagnostic method according to Claim 1 in which sampling of the unloaded electric signal V_μ begins a predetermined period of time after the load signal indicates that the rotating equipment is unloaded.

13. A diagnostic method according to Claim 1 in which the loaded and unloaded electric signals V_ℓ and V_μ correspond to the maximum electric readings taken during said predetermined sampling period of time.

14. A diagnostic method according to Claim 1 in which the loaded and unloaded electric signals V_ℓ and V_μ are respectively summed during said predetermined sampling period of time to generate a loaded index I_ℓ and an unloaded index I_μ, respectively.

15. A diagnostic method according to Claim 1 in which the loaded and unloaded electric signals V_ℓ and V_μ are averaged during said predetermined sampling period of time to generate an average loaded electric signal ∇_ℓ and an average unloaded electric signal ∇_μ, respectively.

16. A diagnostic method according to Claim 1 in which an alert signal corresponding to the arithmetic difference ΔV between V_ℓ and V_μ is generated and displayed visually.

17. A diagnostic method according to Claim 14 in which an alert signal corresponding to the arithmetic difference ΔV between I_ℓ and I_μ is generated and displayed visually.

18. A diagnostic method according to Claim 15 in which an alert signal corresponding to the arithmetic difference ΔV between ∇_ℓ and ∇_μ is generated and displayed visually.

19. A diagnostic method according to Claim 16 in which an alert signal corresponding to the arithmetic ratio R between V_ℓ and V_μ is generated and displayed visually.

20. A diagnostic method according to Claim 17 in which an alert signal corresponding to the arithmetic ratio R between I_ℓ and I_μ is generated and displayed visually.

21. A diagnostic method according to Claim 18 in which the alert signal corresponds to the arithmetic ratio R between ∇_ℓ and ∇_μ.

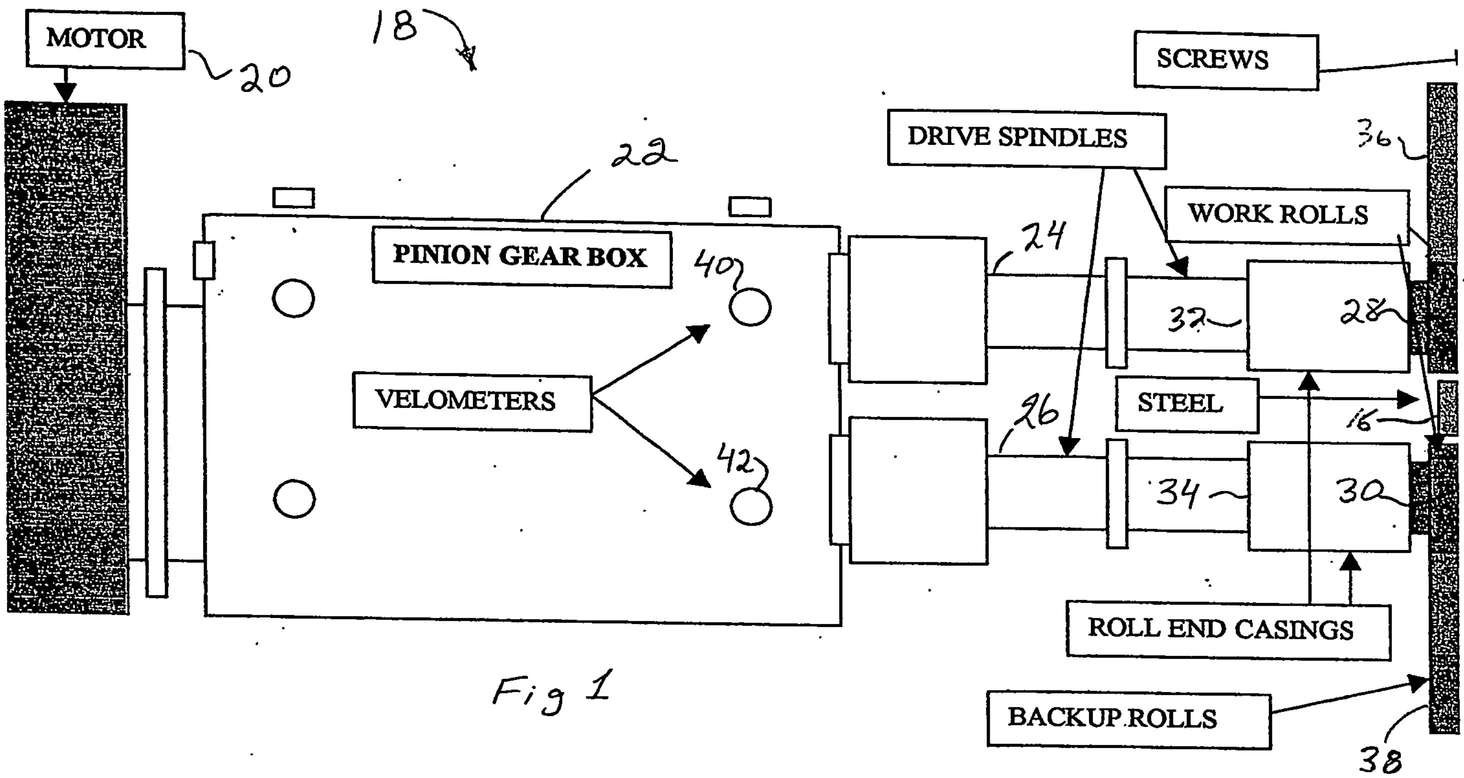
22. A diagnostic method according to any one of Claims 16 to 18 in which a daily average arithmetic difference ΔV is plotted over time.

23. A diagnostic method according to any one of Claims 16 to 21 in which a daily average arithmetic ratio R is plotted over time.

24. A diagnostic method according to Claim 1 in which an alert signal consisting of a plot of the daily average loaded electric signal V_ℓ and a plot of the daily average unloaded electric signal V_μ is made.

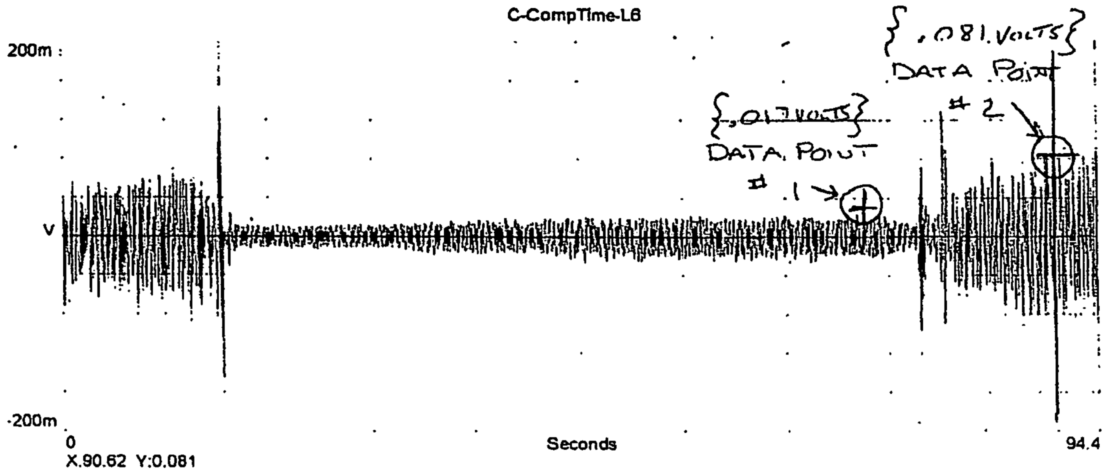
25. A diagnostic method according to any one of Claims 19 to 21 in which the logarithmic of the ratio R is accumulated and monitored.

26. A diagnostic method according to either Claim 22 or 23 in which the slope of the plot is monitored.



MOTOR
20
18
22
PINION GEAR BOX
40
VELOMETERS
42
24
26
DRIVE SPINDLES
SCREWS
36
WORK ROLLS
32
28
STEEL
16
34
30
ROLL END CASINGS
BACKUP ROLLS
38

Fig 1



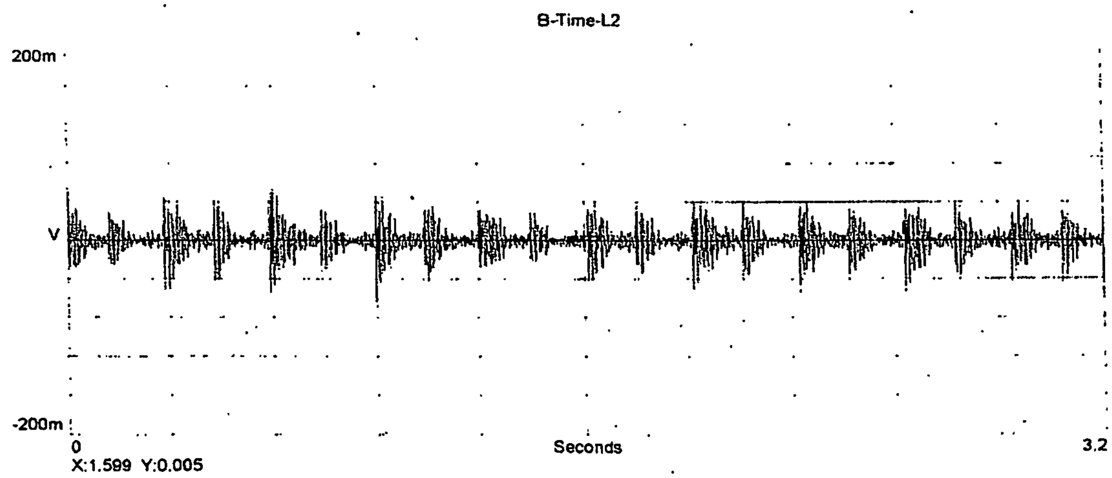
Ch 6 Full Scale . 100 mVrms
Cal Factor 100mV/EU

Display : Compressed Time Trace
Frequency Span . 500 Hz

Size : 120832 Samples
Weighting · Hanning
Overlap : MAX

Domain Cross Properties
Method : Exponential
AVG Count : 0 of 10

WORN SPINDLE Fig 2a



Ch 2 Full Scale : 100 mVrms
Cal Factor : 100mV/EU

Display : Time Trace
Frequency Span : 500 Hz

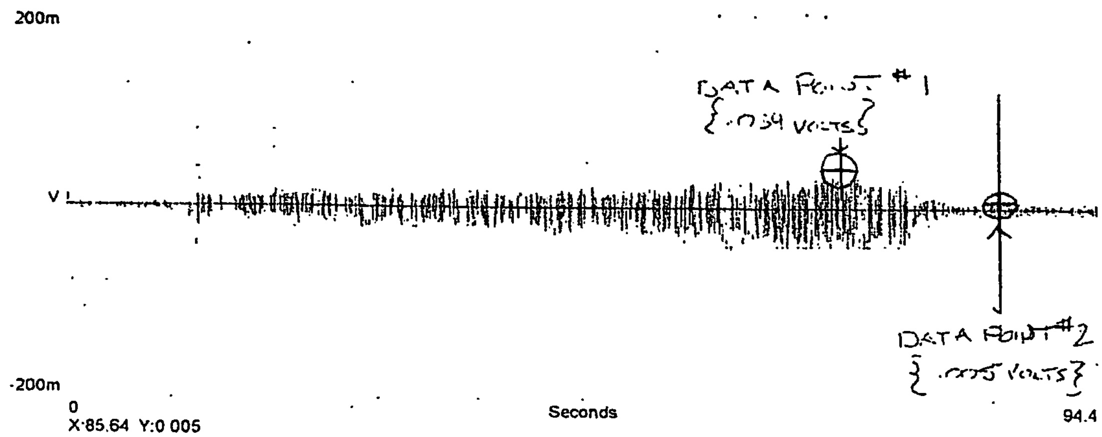
Block Size : 4096 Samples
Weighting : Hanning
Overlap . MAX

Domain : Cross Properties
Method : Exponential
AVG Count : 0 of 10

Data was taken from top accelerometer (XX) as marked in drawing before spindles were changed. Bottom plot shows expanded detail of cursor location on top plot, note that impacting at spindle rotational speed is present.

Fig 2b

F-CompTime-L6



Ch 6 Full Scale 100 mVrms
Cal Factor 100mV/EU

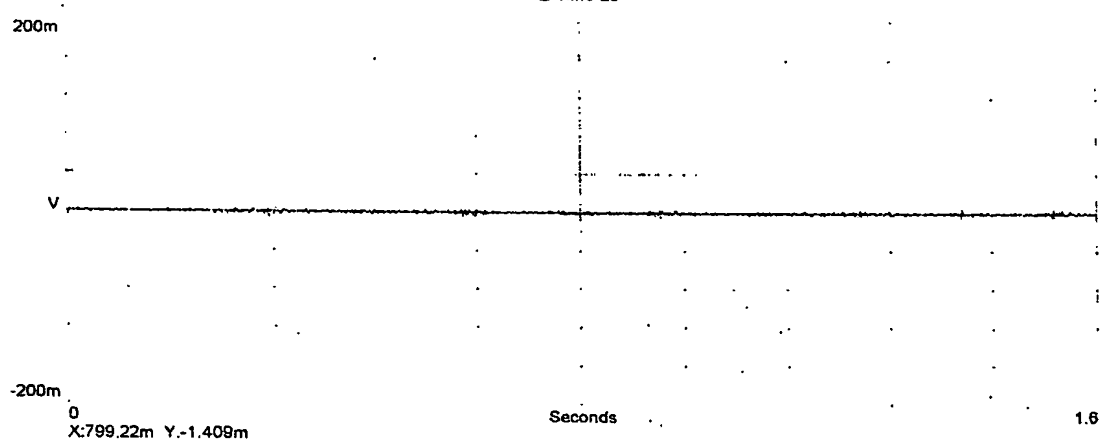
Display : Compressed Time Trace
Frequency Span : 500 Hz

Size 120832 Samples
Weighting : Hanning
Overlap . MAX

Domain . Cross Properties
Method . Exponential
AVG Count 0 of 10

NEW SPINDLE Fig 3a

E-Time-L6



Ch 6 Full Scale . 100 mVrms
Cal Factor 100mV/EU

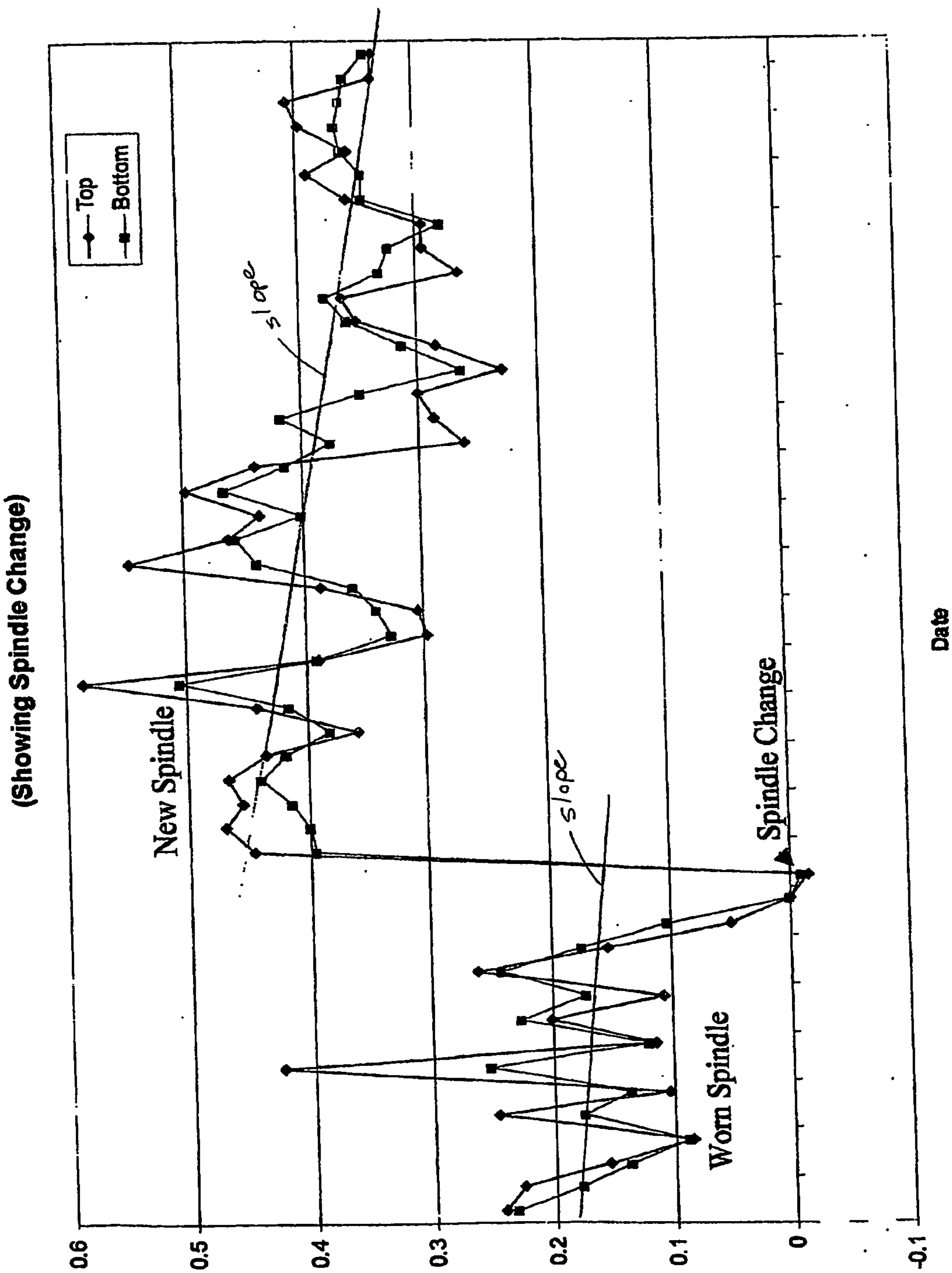
Display : Time Trace
Frequency Span 500 Hz

Block Size : 2048 Samples
Weighting : Hanning
Overlap . MAX

Domain Cross Properties
Method : Exponential
AVG Count : 0 of 10

Data was taken from top accelerometer (XX) as marked in drawing after spindles were changed. Bottom plot shows expanded detail of cursor location on top plot. note that impacting at spindle rotational speed is no longer present.

Fig 3b



(Showing Spindle Change)
Top
Bottom
New Spindle
Worn Spindle
Spindle Change
slope
slope
Date
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1

Fig 4

Chart #1745

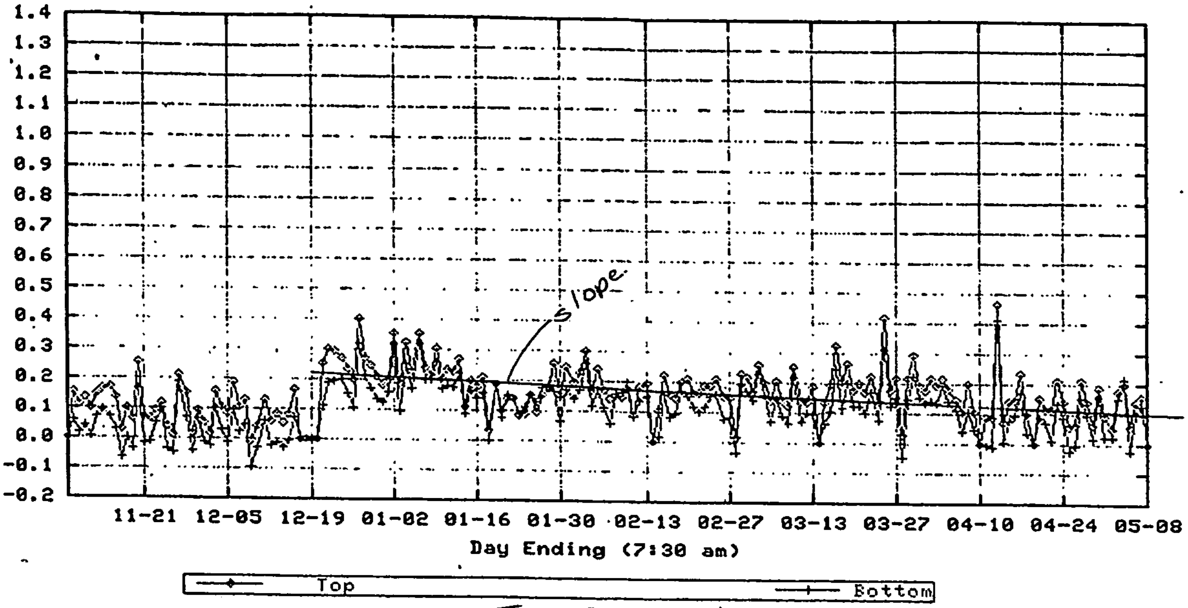


Fig 5

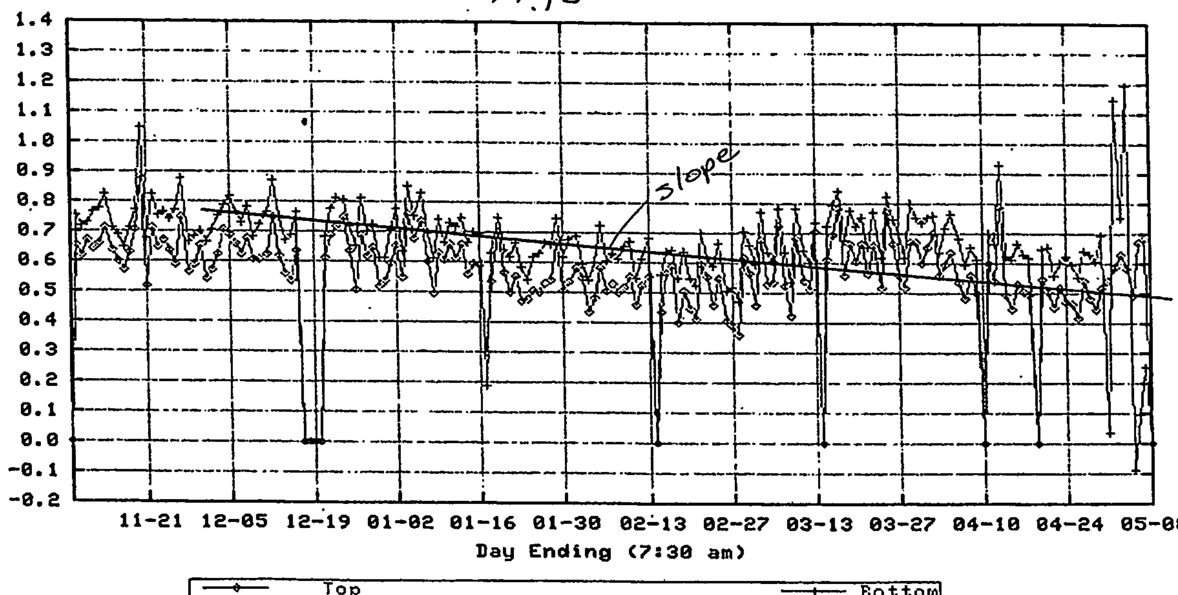


Fig 6

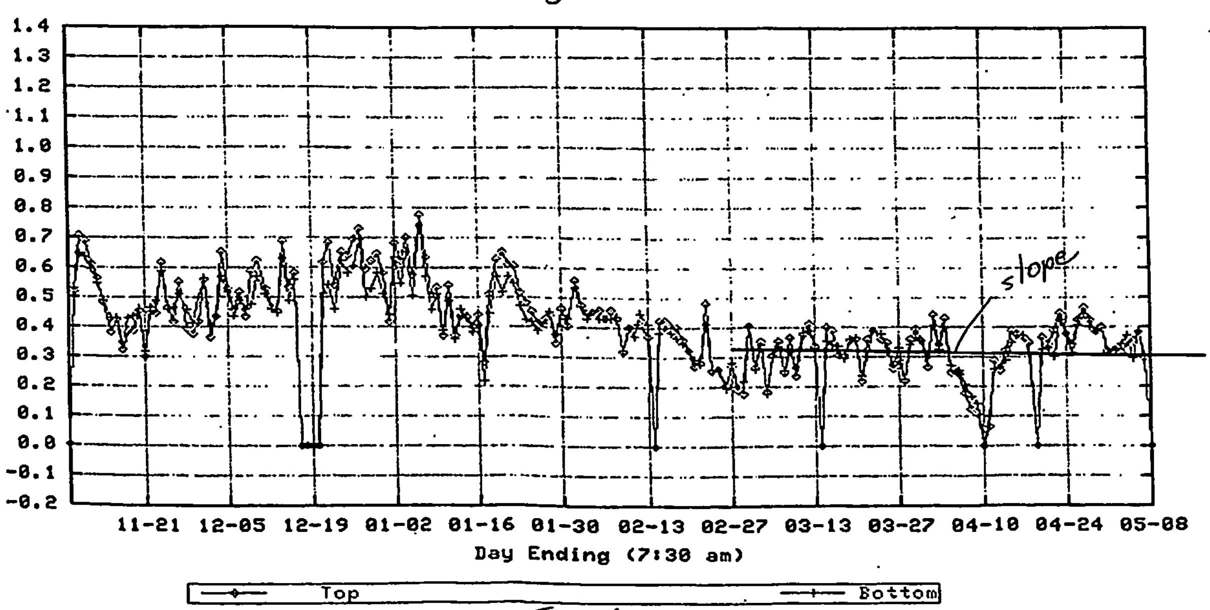


Fig 7

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